Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

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How to cite: Wang W, Zhao M. Effect of Body Postures and Air Ventilation Rates on Air Gap Entrapped in Personal Air Ventilation Garments. Textile & Leather Review. 2024; 7:1234-1251. https://doi.org/10.31881/TLR.2024.124

How to link: https://doi.org/10.31881/TLR.2024.124

Published: 24 July 2024

Effect of Body Postures and Air Ventilation Rates on Air Gap Entrapped in Personal Air Ventilation Garments

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Article

https://doi.org/10.31881/TLR.2024.124

Received 16 May 2024; Accepted 18 July 2024; Published 24 July 2024

ABSTRACT

The article aims to identify the effect of body postures and air ventilation rates on the volume and thickness of the air gap under air ventilation garments (AVGs). The geometric models of the human body and clothing were obtained by using a 3D body scanner. Then the distribution of air gap volume and thickness for five postures (standing, arm flatting, arm lifting, sitting, and trunk bending) and three air ventilation rates (0L/S, 12L/S, 20L/S) were calculated by Geomagic software. The results showed that both body postures and air ventilation rates significantly influenced the air gap entrapped. Among the five postures selected, the air gap thickness (AGT) in the arm lifting posture is always in a thicker state, and when the air ventilation rate reaches high speed (20L/S), the maximum AGT in the chest is 0.086 m, and the maximum AGT in the waist is 0.092 m. This research provides an improved comprehension of the distribution of air gap entrapped in AVGs.

KEYWORDS

air ventilation garment, body posture, air ventilation rate, entrapped air gap

INTRODUCTION

In recent years increasing heat-related illness and mortality have been recorded [1]. People have responded to heat stress during hot periods by proposing various methods to protect people operating in hot environments [2]. Personal cooling garments are one of these methods. There are various types of personal cooling garments, for example, liquid cooling garments [3-5], phase change material garments [6,7], hybrid cooling garments [8], and air ventilation garments (AVGs) [9,10]. In environments without air conditioning (including outdoor environments, environments not suitable for air conditioning, etc.), AVGs provide thermal comfort at an economical cost, and thus AVGs have attracted much interest due to the advantages of being lightweight, portable, and accessible. They can be used by the general population for daily work and some other activities in offices and outdoors.

AVGs are intended to accelerate heat transfer in the “body-garment-microenvironment” system by applying forced ventilation. With a thicker air gap, the air in the microenvironment will flow more smoothly, such as the lower back, and the skin temperature in the corresponding area will be lower [11,12]. On the contrary, in places where the thickness of the air layer is relatively small, such as the shoulder and the front chest, the airflow is slow or even hardly changes, and the relative temperature of the air is higher [13]. For example, Zhao et al. investigated an AVG incorporated with small fans on torso thermal comfort in a moderate environment (Ta = 25 °C, RH = 50%) [14]. The findings indicated a high flow rate dramatically reduced the local skin temperatures in the belly, shoulder blades, and waist ($p<0.05$). Zhang et al. conducted a study on the relationship between micro-fans and inflow air speed [15]. It was found that among them the bottom fan model has the best efficiency and cooling effect. Chen and Zhang conducted a study on thermoelectric cooling and ventilation garments and conventional hybrid cooling garments and found that the average skin temperature was respectively reduced by 1.6 °C and 1.1 °C, in comparison with no cooling [16]. Del Ferraro et al. investigated the cooling effect of a ventilated jacket on a sweating manikin in a wet experiment at a constant temperature (Ts = ta = 35 °C) and showed that the evaporative heat loss increased significantly ($p<0.001$) and that the total evaporative resistance value decreased significantly as the fan velocity [17]. Wang et al. investigated the effect of four cooling strategies on the cooling of a hybrid personal cooling system of phase change materials and electric fans(HPCS), in a high-temperature environment(Tair=36 °C, RH=59%), and found that the control of electric fans could suppress the rise of the average skin temperature of the HPCS to 34 °C for more than 15 minutes [18]. In addition, some studies have shown that the air layer under the garment is an important indicator that affects the heat transfer performance of the garment more than the thickness of the fabric, the surface density, and the thermal conductivity [19]. Emel Mert also clearly pointed out in his study that the air gap thickness (AGT) and the contact surface between the human torso and garments affect the heat transfer in the garment, and that the AGT in contact surface is affected by different postures [20]. The changes in the average thickness of the underclothing air layer in different garments showed similar trends to the changes in the total volume, and the softness of the garment fabric and the effect of gravity also affected the incremental changes in the underclothing air layer at different looseness levels [21]. Thus, the precise determination of optimal air gap thresholds for functional garments is essential.

Meanwhile, changes in body posture can also have an impact on the heat transfer of clothing. It has been shown that changes in body posture can significantly affect the heat transfer in the "body-clothing-environment" system [22,23]. Lou found that the sedentary posture, compared to the standing posture, is more helpful in improving air cooling due to the increased air ventilation in the chest region of the clothing microenvironment [24]. Xu et al. found that the total convective heat transfer coefficient of standing posture is respectively 5% and 20% higher than that of sitting posture [25]. This shows that changes in posture affect the heat exchange between the human torso and the external environment through clothing, which has not been emphasized in AVGs. The quantitative characterization of body posture still needs to be explored to establish a targeted methodology for the study of AVGs.

Hence, we obtained the geometric models of the human body and AVGs by utilizing a three-dimensional body scanner and investigated the air gap volume and thickness distributions of five body postures under three air ventilation rates, which were quickly and efficiently calculated by modelling, alignment, and three-dimensional comparisons with the reverse engineering software Geomagic. These research results can better understand the distribution of air gaps in AVGs under different body postures and air ventilation rates, which can help to design a more reasonable size of the air gap.

EXPERIMENTAL

Materials and Methods

Materials

The fabric used in this research was made of polyester cotton with better breathability to make summer workwear short sleeves. The short-sleeved jacket is made with only one layer. The garment length of the AVG is 68 cm, the chest circumference is 106 cm, the waist circumference is 88 cm, the shoulder width is 46 cm and the sleeve length is 32 cm. The weight of the AVG was 0.912 kg. The AVG was composed of two battery-powered ventilation fans. The two ventilation fans were symmetrically placed on the lower back of the torso and the fans were removable and detachable with a snap-fit. The fans were made of plastic with an inner diameter of 9 cm and an outer diameter of 10 cm. The ventilation fans were powered by a 50,000 mAh, 7.4V Li-ion rechargeable battery. The airflow rate can be 20 L/S and 12 L/S, and the fan can run continuously for 18 - 20 hours at the maximum speed. Fans were the inlets of the airflow and the openings of the jacket were the outlet of the airflow. Figure 1-(a) was the working principle of AVG. When the fans are switched on, environmental air cycle's torso in the microclimate of the garment and the air flow rate can be altered by adjusting the air ventilation rates of the fans.

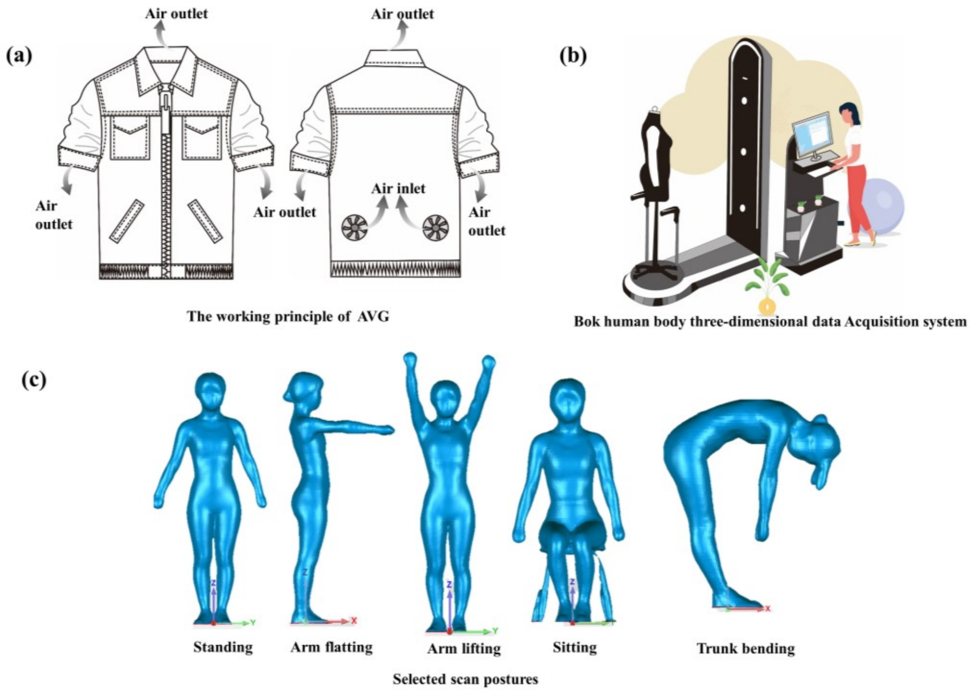

Figure1. (a) Heat transfer phenomena in clothing microenvironment (b) The working principle of AVG (c) Bok human body three-dimensional data Acquisition system (d) Selected scan postures

Experimental instrument and body postures

The Boke 3D human body scanner (Shenzhen Boke Digital Technology Co., Ltd, Guangdong, China) used in this experiment consists of a body sensor composed of an infrared camera and an RGB camera as the scanning component, which performs contactless scanning of the human body. This is illustrated in Figure 1(b), scanning component and turntable can be controlled by software (3D Body Scanning System, Shenzhen Boke Digital Technology Co., Ltd, China) operation, the turntable can be rotated 360°, and combined with the up and down movement of the scanning component, we can get the complete human body data. According to the product instructions of the scanner, the scanner has a scanning accuracy of ≤ 0.15 mm, similarity ≥ 95%.

Five body postures were selected to simulate the human daily activities in this study, we first selected standing and sitting postures as the most common postures in daily life and then selected arm flatting, arm lifting and trunk bending postures typically used by workers at work as representative body postures. The selected scanning postures are shown in Figure 1(c).

Three-dimension scanning and point cloud data processing

We recruited six female university students for 3D scanning. To minimize possible effects of different body features, all recruited participants were of average stature: age = 23 ± 2 years, height =160 ± 5 cm, weight = 50 ± 2 kg, chest circumference = 82 ± 4 cm and waist circumference = 60 ± 2 cm. This study has the approval of an ethics committee.

Each subject was scanned 4 times for each posture, once in their underclothing (nude scans) and three other times in their AVGs with three air ventilation rates (clothed scan). Totally 120 (6 subjects × 4 test samples (1 underclothing and 3 AVGs with three air ventilation rates) × 5 body postures) scans were conducted.

The dynamic insulation of a garment can only be simulated by accurately inputting the thickness of the human body's kinematic closed air gap. The precise measurement of an enclosed AGT can be accurately measured by garment simulation software or 3D scanning methods [26,27]. Within the article, the point cloud data processing and the extraction of the eigenvalues of the underclothing air layer were carried out in Geomagic Control 2014 (3d Systems Inc., Valencia, CA). The raw point cloud data from the naked and clothed scans were initially imported into Geomagic Control to refine and export the complete, smooth 3D images. The naked and clothed images were then merged and aligned in it. The aligned model was compared in three dimensions to obtain the data of average air layer volume and thickness as well as the air layer distribution map, and the two parts of the body, waist, and chest, were selected for two-dimensional deviation comparison based on the three-dimensional comparison, and the results of the comparison were exported [28]. The fitting process of the air layer is shown in Figure 2(a).

According to equation (1), the volume of the naked body is subtracted from the volume of the clothed body to obtain the air gap volume under the clothing.

$$V_{air} = V_{cl} - V_{body} \tag{1}$$

Where V_{air} is the volume of the air gap entrapped, V_{cl} is the dressed human body, V_{body} is the nude human body, and the unit is m^3.

According to equation (2), the thickness of the naked body is subtracted from the thickness of the clothed body to obtain the AGT under the clothing. Figure 2-(b) illustrates the AGT at the waist and chest.

$$T_{air} = T_{cl} - T_{body} \tag{2}$$

Where T_{air} is the thickness of the air gap entrapped, T_{cl} is the dressed body human, T_{body} is the nude human body, and the unit is m.

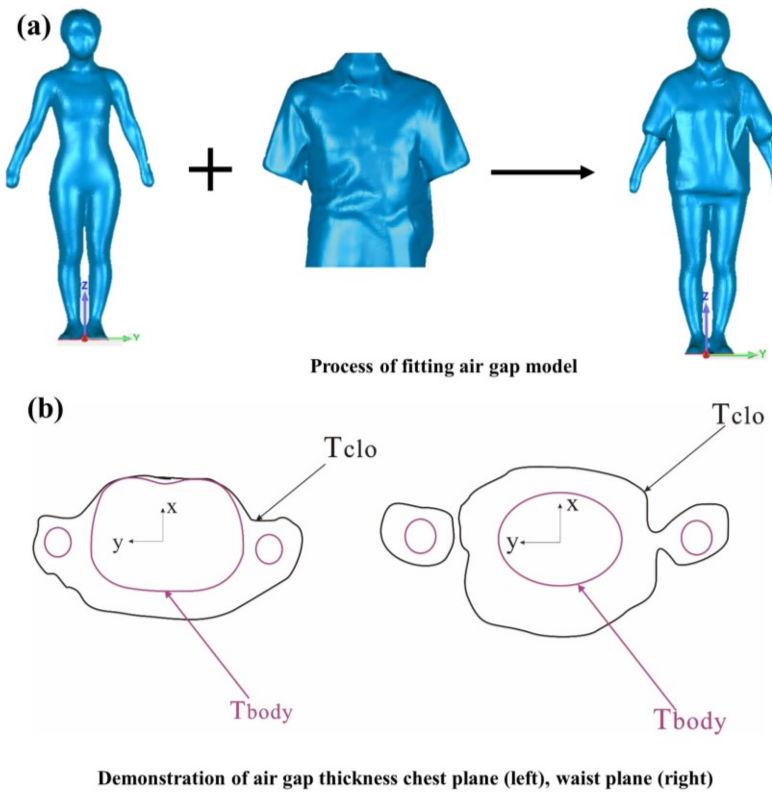

Figure 2. (a) Process of fitting air gap model (b)Demonstration of air gap thickness chest plane (left), waist plane (right)

Data analysis

SPSS Statistics 24.0 (IBM, SPSS Inc. USA) was used to conduct normal tests and variance homogeneity analysis on the air gap size quantitative data of 6 subjects. Shapiro-Wilk normality test was used in this study. ANOVA was employed to compare air gaps under clothing between five body postures and three air ventilation rates. Each statistical test was performed with a 0.05 level of significance.

RESULTS AND DISCUSSION

Distribution of the AGT and volume with different postures and air ventilation rates

As shown in Figure 3, a comparison of the air gap entrapped on the side of the garment with the fan off and on, it can be observed that the underclothing air gap volume and distribution of the air layer were significantly changed after applying forced ventilation inside the clothing. According to the research of Zhao et al. on the cooling performance of the air ventilation garment in a constant environment (34 °C, 69% RH, and 0.20 m/s), It can be noticed that the air gap volume increased from 0.014 m^3 to 0.019 m^3 when the fan goes from off to on [29]. Thus, forced ventilation will have a high impact on the distribution of underclothing air gaps. At the same time, the average air gap volume and thickness between clothing and human torso were obtained by processing the experimental data with different air ventilation rates and postures.

Figure 3. Comparison of air gap entrapped on the side of the garment with fan off and on

The average air gap volume and thickness of five different body postures under different air ventilation rates are shown in Figure 4. The results showed that the average air gap volume of the ventilated jackets studied in this paper ranges from 0.009 to 0.023 m^3, and the average AGT of the ventilated jackets ranges from 0.021 to 0.068 m. Findings show a linear increase in the overall air gap as the air ventilation rate increases. Ankit Joshi et al. [30] investigated the variation in AGT during walking movement consisting of standing (0 m/s) and two walking speeds (0.27 m/s, and 0.69 m/s), three ambient air speeds: still air (0.17 m/s), 1 m/s and 2 m/s, calculated the quantification of AGT in the human upper body was 0-0.07 m which is highly consistent with our research results in the following Figure 4(a).

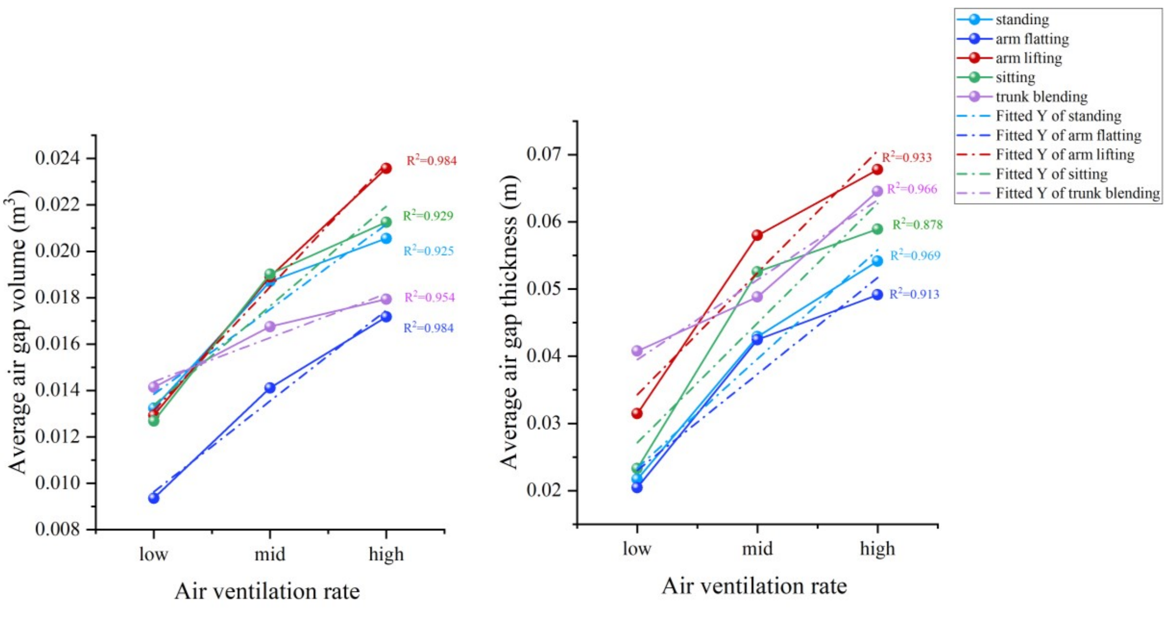

Figure 4. Average air gap volume and thickness under different air ventilation rates and postures

What's more, in standing posture, the mean air gap volume ranged from 0.013 to 0.020 m^3 and the AGT ranged from 0.021 to 0.054 m^3. The air gap volume in the sitting and arm flatting posture were about the same as in the standing posture, both ranging from 0.009-0.021 m^3. The arm lifting posture had the largest mean air gap volume, ranging from 0.12 to 0.023 m^3, while the trunk bending posture had the smallest mean air gap volume, varying from 0.014 to 0.017 m^3. The variation rule of AGT is the same as that of air gap volume. This finding indicated that when lifting the arms higher, the air gap becomes higher with more evenly distributed as the air ventilation rates increase. Wang et al. using three-dimension scanning and Geomagic analysed the AGT in three test coverall garments and seven selected postures, they found that the bending posture was the least AGT, ranging from 0.003 m to 0.016 m, in standing posture, the mean AGT was ranging from 0.007 m to 0.027 m. In arm lifting postures, the mean AGT was between 0.003 m and 0.028 m [13]. The reason the AGT values are smaller than ours is that Wang's study was coverall garments without a fan. But it can also be found from their research that bending posture was the least AGT.

According to the results of the normality test, the mean air gap volume with different postures and air ventilation rates conformed to normal distribution. After that, the F-test was conducted and the test result was variance-aligned. Finally, one-way ANOVA was conducted, and the different postures and air ventilation rates both significantly affected the mean air gap volume but the interaction between postures and air ventilation rates did not significantly affect the mean air gap volume. In addition, according to the results of descriptive statistics, the most important influence on the mean air gap volume was observed when the posture was the arm lifting posture and the air ventilation rate was 20 L/S (high speed).

Impact analysis of the overall air gap distribution

Figure 5 illustrates the distribution of air layers on the front and back of the human torso under different postures. From the backside distribution plot, it can be seen that when the fan is turned on, the air gap is thicker at the folds formed on the backside due to the draping of the garment fabric, showing a more regular cylindrical shape. However, Psikuta et al. measured the AGT within 3D scanning and Geomagic Qualify, the results showed the air gap is likely to become narrower when the garment drapes down rather than forming a regular cylinder at the torso area [31]. The reason for this discrepancy may be that the opening of the two fans was in the back of the experimental garment combined with the use of an elasticized closure at the hem of the garment made the shape of the folds more regular when the fans blew up. On the one hand, as expected, the switching on and off of the fans can significantly affect the air gap entrapped distribution. In the study of Zhao et al. on the cooling performance of air ventilation garments in a constant environment (34 °C, 69% RH, and 0.20 m/s), they also found that the switch of the fan can significantly affect the air gap, especially in the waist and back

[29]. When the fan was turned on, the air layers at the chest, waist, and mid-back were significantly larger and more evenly distributed. Takada et al. used CFD analyses to observe air distribution within and around clothing, for adults wearing a single layer of clothing under typical indoor environmental conditions, it can be noticed that as air permeates through the garment, the air gap underneath the garment is more evenly distributed [32]. As the air ventilation rate increases, the red area on the back increases, which means the AGT increases. Yang et al. investigated the effects of three garment sizes(S, M, L) and two ventilation volumes((LV, 12 L/S and HV, 20 L/S) on the performance of a ventilated jacket, it can also be seen that the amount of air ventilation significantly increased the total U_{Body} heat loss ($p<0.05$) [33]. On the other hand, it can be observed that the change of postures has some effect on the air gap entrapped. It can be found that the arm lifting posture always has the largest AGT and the air gap distribution is more even. The trunk bending posture causes the AGT on the back to decrease and the thickness on the front to increase due to gravity. Psikuta et al. investigated the differences in the distribution of air gap in firefighters' garments in three postures, (crawling, holding a hose, and standing), they also found that crawling over resulted in the deformation of clothing and a significant increase in the AGT in chest and abdomen [34].

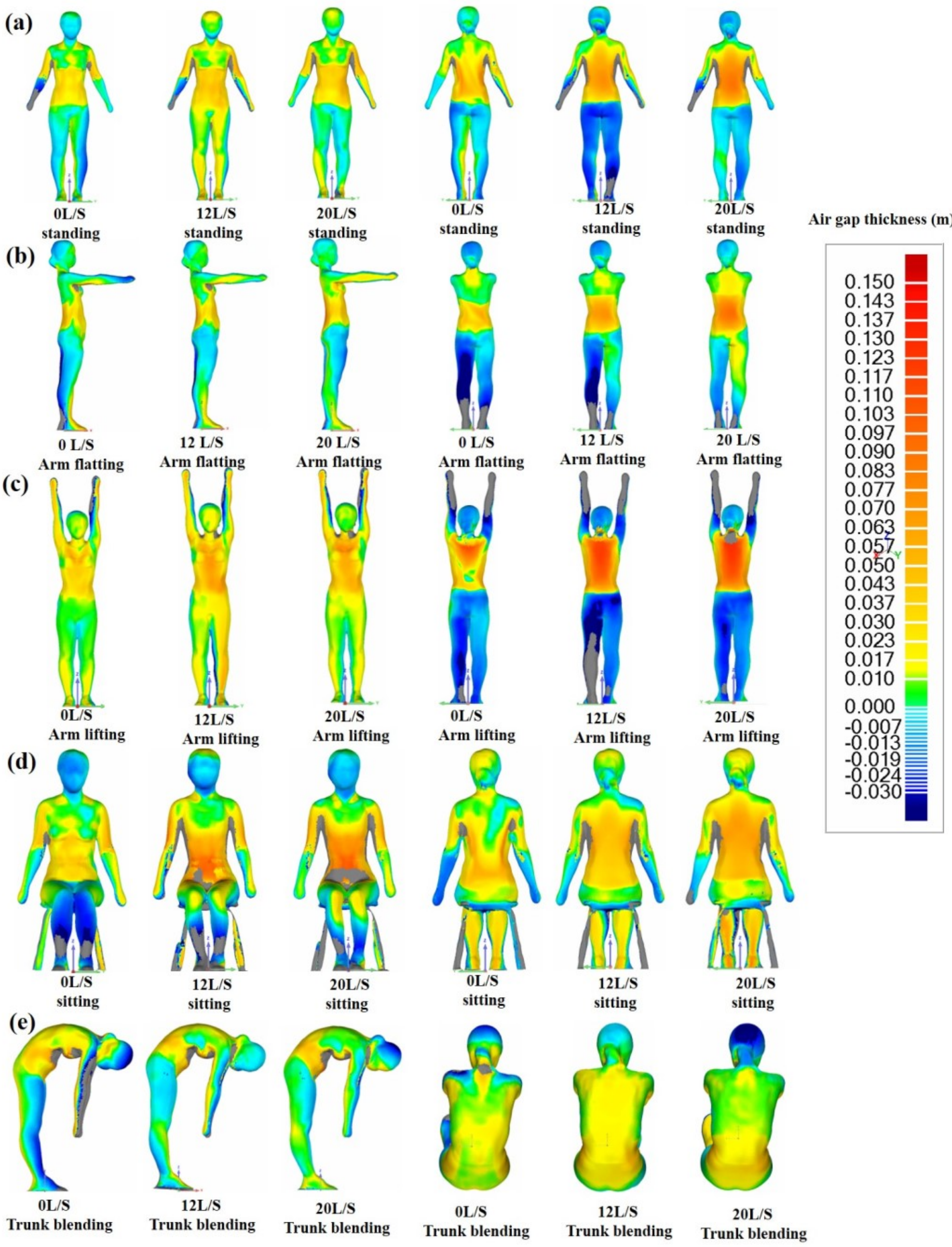

Figure 5. Distribution of air gap thickness on torso part in different fabrics ventilation garments in front and back view

Impact analysis of localized air gap distribution

Based on 3D comparison, two parts with more obvious features, namely the chest and the waist were selected to compare the 2D air layer distribution under different conditions, and to analyze the variation in thickness and spread across the air gap entrapped as well as the average thickness of air gap entrapped in these two parts. The chest was set with a distance of 1.23 m from the Z-axis of the system coordinate axis and the waist was set with a distance of 1.07 m (the position degree of the bottom of the model is 0). Figure 6 shows the air layer distribution of the chest and waist under different postures. As can be seen from Figure 6, compared with other body parts, the air gaps in the waist are the largest. Wang also found that differences in body geometry and clothing styles resulted in uneven distribution of air layers throughout the body, for example, the waist had the largest average air layer, followed by the shoulders [13]. This may be because the waist of the human body presents a concave curvature, which causes the clothing to overhang at a certain distance from the body, creating a larger air layer. The average air gap in the chest and waist increases significantly when the fan is turned on, and the AGT in these parts increases with the increase of the fan air ventilation rate and is distributed more uniformly. The wearing condition of the clothing and the curved shape of the body surface have a greater influence on the thickness and distribution of the air layer. According to Lou's research, it was found that because the curvature of the chest and back are different, it causes changes in the air layer under the garment [24]. At the same time, it can also be observed that due to the different postures of the human body, the clothes will be deformed, which will cause the shape of the air layer to change. As observed in Figure 6, the AGT of the chest and waist was thicker when the arm was lifted, and when the air ventilation rate reached 20 L/S, the air layer distribution became more uniform. This is because the arm lifting posture makes the air circulation in the upper body more unhindered, so the shape of the air layer became more regular.

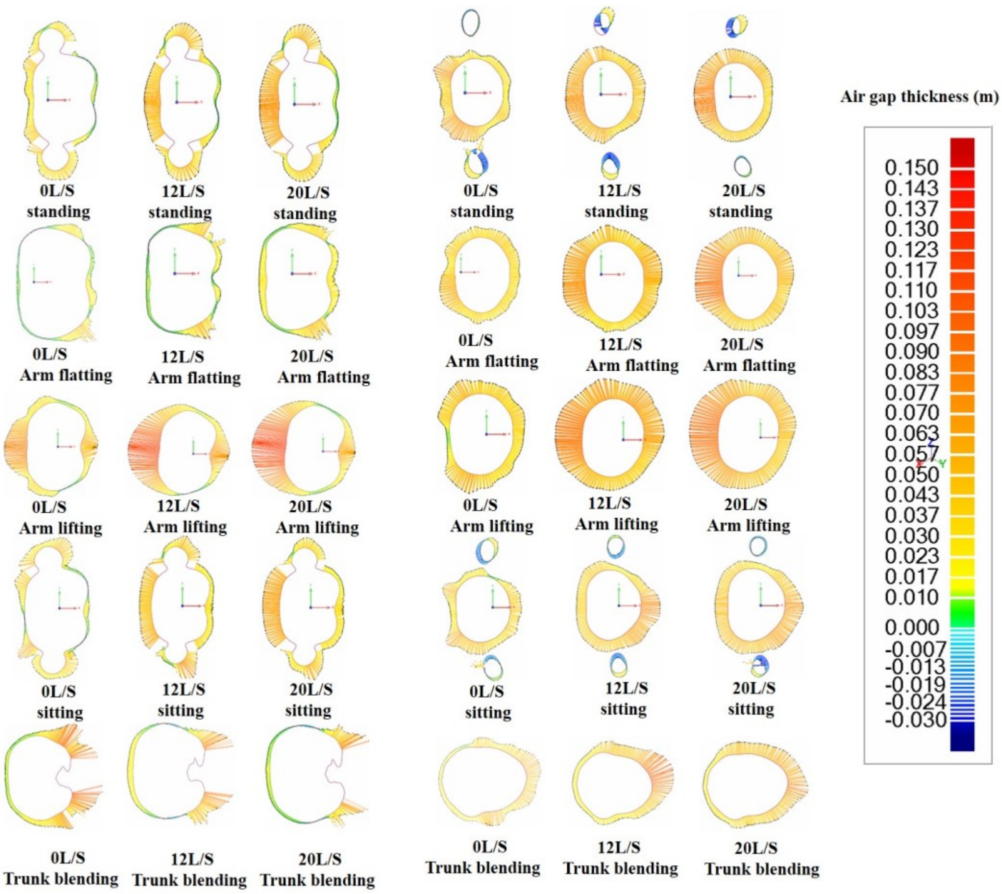

Figure 6. Air gap distribution maps at chest and waist level in different postures

Air gap distribution at localized points

As shown in Figure 7, based on the two-dimensional comparison, four human body points at the chest position are selected, which are the anterior centre point (A point) the posterior centre point (B point), the chest point (C point) and the point directly behind the chest point (D point). Two points at the waist are selected, which are the centre point of the waist (E point) and the point directly behind it (F point). These six human body points are selected to compare their two-dimensional air gap distribution under different conditions and analyse the thickness of the air gap and distribution of these six points.

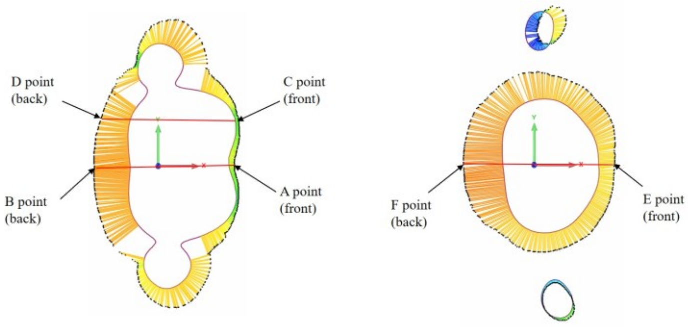

Figure 7. Chest (left) and Waist (right) air gap thickness measuring points

According to the results of the significance analysis, as shown in Table 1, different postures and air ventilation rates had a significant influence on the AGT under six points at the chest and waist ($p<0.05$), the interesting fact is that the interaction of posture and air ventilation rate also significantly on the AGT at chest B point and chest D point ($p<0.05$).

Table 1. Influence of postures and air ventilation rates on air gap thickness at localized points

Air gap thickness (AGT)	F- value			P- value		
	Postures	Air ventilation rates	Postures × Air ventilation rates	Postures	Air ventilation rates	Postures × Air ventilation rates
Chest point A	16.372	5.008	1.237	0.000*	0.009*	0.749
Chest point B	37.843	20.686	3.162	0.000*	0.000*	0.005*
Chest point C	28.291	5.751	0.478	0.000*	0.004*	0.868

Air gap thickness (AGT)	F- value			P- value		
	Postures	Air ventilation rates	Postures × Air ventilation rates	Postures	Air ventilation rates	Postures × Air ventilation rates
Chest point D	16.592	22.564	2.108	0.000*	0.000*	0.045*
Waist point E	10.864	8.808	0.599	0.000*	0.000*	0.776
Waist point F	12.153	34.798	1.630	0.000*	0.000*	0.130

As shown in Figure 8 (a)-(d), with the change of air ventilation rate from low speed to mid speed, the AGT in different postures at chest points A-D ranged from 0.02 m to 0.08 m. The AGT at chest point C is between 0-0.03 m. The reason that chest point C is much lower than the other points is because the fans were mounted on the back and the shape of the chest bulge resulted in the forced convection of the fans not being very significant. In addition, at the air ventilation rate of high speed, the AGT in the arm lifting posture was always relatively high and could reach a maximum of 0.09 m. The AGT in different postures increased to different degrees as the air ventilation rate continued to increase. In addition, the AGT at the waist was also tested, this is illustrated in Figure 8 (e) - (f). The AGT at points E and F of the waist were mainly in the range of 0.02 m - 0.09 m, and when the air ventilation rates were mid and high speed, the AGT at point F was generally larger than that at point E, which was mainly attributed to the installation position of the fan. Moreover, the AGT at the waist was overall thicker than that at the chest, again because a fan was installed in a position where it could blow directly to the waist.

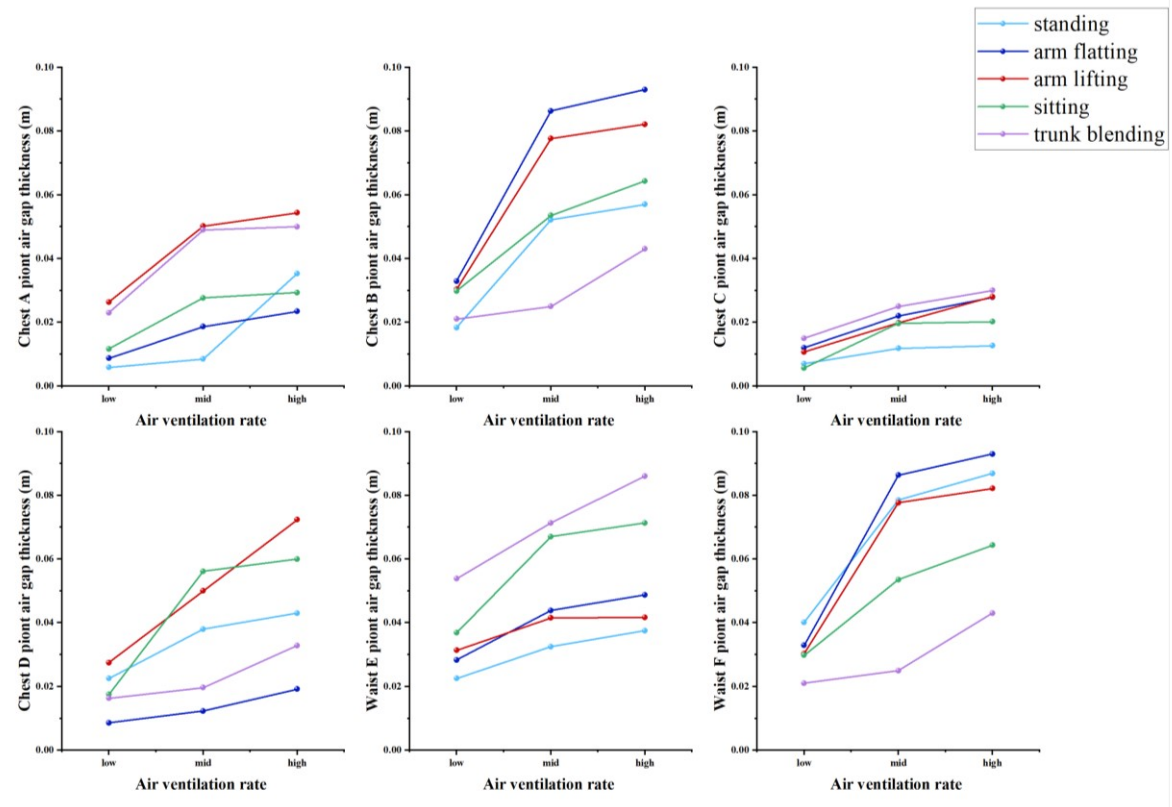

Figure 8. The air gap thickness on chest and waist points. (a) Chest A point, b Chest B point, (c) Chest C point, (d) Chest D point, (e) Waist E point, (f) Waist F point

The reason for the difference in AGT at different locations is the structure of the female body. The AGT of waist points is higher than chest points which is attributed to the position for fan installation. In addition, according to the study of Mert et al., it can be found that the thickness of the air layer is indeed affected by human posture, and in the upper body, the influence on the waist is more significant, which is consistent with the conclusion of this study [20].

In addition, this study has some limitations, in terms of subjects only some female subjects with similar physical characteristics were selected, in future research it is possible to study people with different physical characteristics and it can be expanded to include the male population. Alternatively, the number of subjects can be increased to ensure the generalizability and accuracy of the experimental results. Also, different types of AVGs such as different shapes of air vents, other air volumes, other fan positions, etc., which may change the air layer in the jacket, can be studied in depth based on this study.

CONCLUSION

In this study, the geometric models of the human body and AVGs were built via a three-dimensional body scanner. The volume and thickness of air gap entrapped distributions during different body postures and ventilation volumes were analysed. Findings show both different postures and the air ventilation rate have a significant effect on the air gap volume and thickness. Different body postures will lead to the deformation of the garment, which will make the shape of the air gap change. Among the five postures selected, the AGT during arm lifting posture is always in a thicker state, and when the air ventilation rate reaches high speed (20L/S), the maximum AGT at the chest is 0.086 m and at the waist is 0.092 m. During trunk bending posture, the AGT at point E of the waist reached 0.084 m, which is the highest point due to the gravity force of the fabric. As the amount of ventilation increases, both the air gap volume and thickness become larger and the air gap distribution becomes more uniform. When the air ventilation rate up to 20 L/S was the most significant effect, we can consider appropriately increasing the air ventilation rate in the future design of AVGs. In conclusion, this research provides an improved comprehension of the distribution of air gap entrapped in AVGs.

Author Contributions

Conceptualization – Wang W; Methodology – Wang W, Zhao M; Formal analysis – Wang W, Zhao M; Investigation – Wang W, Zhao M; Writing-original draft preparation – Wang W; Writing-review and editing –Zhao M; Visualization – Wang W, Zhao M; Supervision – Zhao M. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Human research subjects

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Shanghai University of Engineering Science (NO.EST-2023-014).

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